

Spectrum and ionization rate of low energy Galactic cosmic rays

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2 March 2013

ABSTRACT

We consider the rate of ionization of diffuse and molecular clouds in the interstellar medium by Galactic cosmic rays (GCR) in order to constrain its low energy spectrum. We extrapolate the GCR spectrum obtained from PAMELA at high energies (≥ 200 GeV/nucleon) and a recently derived GCR proton flux at 1–200 GeV from observations of gamma rays from molecular clouds, and find that the observed average Galactic ionization rate can be reconciled with this GCR spectrum if there is a low energy cutoff for protons at 10–100 MeV. We also identify the flattening below a few GeV as being due to (a) decrease of the diffusion coefficient and dominance of convective loss at low energy and (b) the expected break in energy spectrum for a constant spectral index in momentum. We show that the inferred CR proton spectrum of $\Phi \propto E_{kin}^{-1.7 \pm 0.2}$ for $E_{kin} \leq \text{few GeV}$, is consistent with a power-law spectrum in momentum $p^{-2.45 \pm 0.4}$, which we identify as the spectrum at source. Diffusion loss at higher energies then introduces a steepening by $E^{-\alpha}$ with $\alpha \sim 1/3$, making it consistent with high energy measurements.

Key words: ISM: molecules - clouds - cosmic rays.

1 INTRODUCTION

The interaction of cosmic rays (CR) with interstellar material is a powerful probe of the spectrum, and consequently of the origin, of Galactic CR. CR particles ionize the interstellar atoms and molecules, and the ionization rates can be inferred from the abundance studies of different species, such as H_3^+ (McCall et al 2003; Indriolo et al. 2007; Goto et al. 2008). They also spallate interstellar nuclei such as C, N, and O, to create light-element isotopes of Li, Be and B (Reeves et al. 1970; Meneguzzi et al. 1971). CRs also excite nuclear states of certain nuclei and produce gamma-ray lines, as well as produce gamma-rays from pion decay after interacting with interstellar protons (Meneguzzi & Reeves 1975; Issa & Wolfendale 1981).

These interactions provide a method of probing the spectrum of Galactic CRs at low energy where direct observations suffer from the effect of solar modulation. Since these interactions depend on known cross-sections and an

assumed extrapolation of the CR spectrum to low energies, such studies have yielded valuable constraints on the low energy CRs. The observed light element abundances have been used in this regard (e.g., Meneguzzi et al. 1971; Vangioni-Flam et al. 1996; Kneller et al. 2003), as well as gamma-ray lines (Meneguzzi & Reeves 1975; Ramaty et al. 1979; Cassé et al. 1995; Fields et al. 1996; Tatischeff & Kiener 2004), in addition to ionization rates (Hayakawa et al 1961; Spitzer & Tomasko 1968; Nath & Biermann 1994; Webber 1998).

The observed determination of hydrogen ionization rate in diffuse interstellar medium (ISM) ζ^H ranges between a few 10^{-17} s^{-1} to a few 10^{-16} s^{-1} , based on the abundance measurements of various species such as OH and HD (Black & Dalgarno 1977; van Dishoeck & Black 1986; Federman et al. 1996). These inferred rates however depend strongly on various assumptions such as that of the background UV radiation field. It has been shown that a cosmic ray spectrum with a low energy cutoff ~ 50 MeV can explain the observed rates (Spitzer & Tomasko 1968; Nath & Biermann 1994). For ionization of molecular hydrogen, the standard conversion rate of $1.5\zeta^{H_2} \approx 2.3\zeta^H$ (Glassgold & Langer 1974) then

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predicted $\zeta^{H_2} \leq 10^{-17} \text{ s}^{-1}$. The observed value of ζ^{H_2} in molecular cloud cores however ranged between 10^{-17} – 10^{-15} s^{-1} (Caselli et al. 1998), with the values in high density cloud cores being ζ^{H_2} a few times 10^{-17} s^{-1} (van der Tak & van Dishoeck 2000).

Recently, a high ionization rate ($\sim 4\text{--}6 \times 10^{-16} \text{ s}^{-1}$) has been determined in diffuse clouds through the abundance measurement of H_3^+ (McCall et al 1998; McCall et al 2003; Indriolo et al 2007; Goto et al. 2008). The simplicity of reactions involving H_3^+ makes this a robust determination. There appears to be a range of observed molecular ionization rates from diffuse clouds with low molecular content to that in dense clouds. Gerin et al. (2010) and Neufeld et al. (2010) found an ionization rate of $0.6\text{--}2.4 \times 10^{-16} \text{ s}^{-1}$ in diffuse clouds with low molecular content ($H_2/H \leq 10\%$), whereas Indriolo et al. (2010) have found an ionization rate as large as $\sim 2 \times 10^{-15} \text{ s}^{-1}$ near the supernovae remnant IC 443. The contrast between the low ionization rate in molecular cloud cores and the high rate in diffuse clouds can be reconciled by either postulating that CRs are inhibited in dense molecular clouds by some plasma processes, or that there is an additional low energy component in the diffuse component of CRs which cannot penetrate the dense cloud cores (Padovani et al 2009; Indriolo et al. 2009).

Recently Neronov et al. (2012; hereafter referred to as NST12) have determined a spectrum of Galactic CR protons down to a kinetic energy of $\sim 1 \text{ GeV}$, using the observed gamma ray emission from nearby molecular clouds at the Gould’s belt, and normalizing the flux at high energy ($\geq 200 \text{ GeV}$) to the flux determined by PAMELA. They found that in order to explain the observed gamma ray spectrum, the CR proton spectrum requires a spectral break around 9 GeV , below which it becomes shallow. The low energy shape of the spectrum derived by NST12 is interesting with regard to the above discussion of high ionization rate ζ^{H_2} in that the low energy flux is substantially enhanced above the flux extrapolated from high energies. NST12 interpreted the shape of the low energy spectrum as being due to the interaction of CRs with interstellar material in the last $\sim 3 \times 10^7 \text{ yr}$ while traversing a distance of $\sim 1 \text{ kpc}$ from Gould’s belt. In this paper, we suggest another possibility, that the break arises from a combination of (a) the source spectrum being a power-law in momentum, and (b) the dominance of convective loss over diffusion at low energies. We then extrapolate this spectrum down to a low energy cutoff below which we assume the CR flux to be negligible, and compare the predicted ionization rate with the average observed Galactic ionization rate.

Becker et al. (2011) recently considered the ionization rate by CRs in molecular clouds (MCs) close to supernova remnants (SNRs) which are believed to accelerate CRs. They extrapolated the theoretically predicted CR spectrum from shock acceleration mechanism, down to MeV energies, and calculated the predicted ionization rate as a function of a low energy cutoff, which they used to predict abundance of (and emission line strengths from) species such H_2^+ . In a related paper, Schuppan et al. (2012) considered a few MCs associated with SNRs, and determined the CR spectrum from the observed gamma-ray spectrum, assuming a break at 1 GeV and then going down to a low energy cutoff of order $30\text{--}100 \text{ MeV}$. Then they calculated the corresponding

ionization rate in the MCs, which they found to be larger than the Galactic average in a few cases.

Our line of approach is different from these. We adopt the spectrum of CRs determined by NST12 as the average Galactic CR spectrum, and calculate the average ionization rate, which we compare with the observed average ionization rate and discuss the possible low energy cutoff for the average Galactic CR flux. Since this CR spectrum is different from the ones adopted by recent authors, with a spectral break at $E_b \sim 9 \text{ GeV}$ and with a steeper spectral index between E_b and $\sim 200 \text{ GeV}$, the corresponding ionization rate cannot be easily translated from other works. Our goal here is therefore to consider the average Galactic CR flux and compute its ionization rate and compare with the ionization rate in molecular clouds *not* associated with SNRs.

2 SPECTRUM OF LOW ENERGY GCR

The CR spectrum derived by NST12 has a spectral index $\Gamma_2 = 3.03^{+0.37}_{-0.18}$ above a break at $E_b = 9^{+3}_{-5} \text{ GeV}$, and a spectral index $\Gamma_1 = 1.9^{+0.2}_{-0.9}$. The authors state that including a component of bremsstrahlung to the gamma-ray emission reduces the low energy spectral index to $\Gamma_1 = 1.7 \pm 0.2$. The inverse Compton contribution is likely to be negligible if there is no star forming region in the MC. Gabici, Aharonian & Casanova (2009) have estimated that inverse Compton loss becomes significant only if there is an OB association with a total output of $\sim 4 \times 10^{33} \text{ erg/s}$ located in the MC. In this case of MCs considered by NST12, there are no SNRs associated with them, and we assume that inverse Compton loss is not significant. After inferring the spectral indices from gamma ray emission, NST12 normalizes the CR spectrum with the high energy measurement $\geq 200 \text{ GeV}$ with PAMELA (Adrinai et al. 2011).

We note that the CR spectrum inferred at high energy ($E_{kin} \geq 10 \text{ GeV}$) by NST12, with spectral index of $3.03^{+0.37}_{-0.18}$ is consistent with **or close to** that measured by different experiments. For example, PAMELA finds a spectral index of ~ 2.85 for protons in the range of $80\text{--}230 \text{ GeV}$ (Adriani et al. 2011). **However** AMS measured an index of 2.78 ± 0.009 at $10\text{--}200 \text{ GeV}$ (Aguilar et al. 2002), BESS an index of 2.732 ± 0.011 at $30\text{--}few \text{ hundred GeV}$ (Haino et al. 2004), and CREAM measured an index of $\sim 2.66 \pm 0.02$ between $2.5\text{--}250 \text{ TeV}$ (Yoon et al. 2011).

The expected spectrum of CRs from diffusive shock acceleration is a power-law in momentum (p) (e.g, Bell 1978; Drury 83; Blandford & Eichler 1987 and references therein). Although at high energies the corresponding spectral index in energy is the same as that for momentum, since $E \propto pc$, there is expected to be a break in the energy spectrum at a few GeV , with a different spectral index for the low energy CRs, for which one should use $E_{kin} = \sqrt{p^2 c^2 + m^2 c^4} - mc^2$ instead of the approximation of $E \sim pc$. We show in Figure 1 that a spectrum of $\Phi(p) \propto p^{-2.45}$ shows a break in the spectrum in kinetic energy at a few GeV , with the low energy spectral index being ~ 1.7 , and recovering the index of 2.45 at higher energies. **The figure shows that the energy spectrum changes at $\sim \log_{10}(E_{kin}/m_p c^2) \leq 0.6$, or $E_{kin} \leq 3.7 \text{ GeV}$, that lies in the range of measurement of NST12 ($E_{kin} \geq 2 \text{ GeV}$), and is comparable to the lower $(1-\sigma)$ error margin of the break en-**

ergy E_b (9–5 GeV). Our choice of the spectral index is aimed at recovering the inferred index of 1.7 at low energies by NST12. The uncertainty in the inferred spectral index (-1.7 ± 0.2) translates to an uncertainty in the momentum spectral index of -2.45 ± 0.4 .

We also note that the diffusion coefficient of CRs in the ISM is thought to be energy dependent, and this energy dependence steepens the observed CR spectrum compared to the source spectrum. For protons ($Z = 1$), the diffusion coefficient at high energies scales as $D \propto v p^\alpha$, where α depends on the nature of turbulences which scatter the CRs, $\alpha \sim 1/3$ for Kolmogorov-type spectrum of turbulence (e.g., see §2 in Ptuskin et al. 2006). At low energies, the diffusion coefficient becomes independent of energy below an energy of ~ 3 GeV (for protons, with $Z = 1$), as suggested by the observed ratios secondary to primary nuclei (Ptuskin et al. 2006). However, as Biermann et al. (2001) have suggested, convective transport is likely to become more dominant than diffusive ones since it is faster, at energies \leq few GeV/n. **In other words, the mode of cosmic ray transport likely changes at $E_{kin} \sim$ few GeV/n, with convection dominating at low energies and diffusion at high energies.** Therefore, if we identify $p^{-2.45 \pm 0.4}$ as the source spectrum, then (a) at low energies (a few GeV/n), diffusion loss does not steepen the spectrum, and we get a spectral index of -1.7 ± 0.2 in kinetic energy, and (b) the high energy spectrum will steepen by $d\gamma \sim 1/3$, rendering an index $\sim -2.8 \pm 0.4$, consistent with the high energy measurements as mentioned above, especially the AMS data. Also, the inferred spectral index at source is consistent with theoretical predictions (see, e.g., Biermann 1993).

NST12 proposed that the break below ~ 10 GeV arises either because of p-p interactions with ISM or scattering from magnetic inhomogeneities which may be dominated by clouds of a certain size (~ 1 AU). However, from the p-p interaction argument, the time scale is $\sim 3 \times 10^7$ yr, much larger than the typical residence time scales of GCR inferred from other considerations.

In view of the **arguments** presented above, which makes two reasonable assumptions: (a) that the source spectrum of CRs is a power-law in momentum and that (b) the diffusion coefficient becomes energy independent and/or becomes sub-dominant compared to convective transport, below ~ 5 GeV, we find that the NST12 spectrum can be explained without recourse to any additional processes, *although one cannot rule out other processes contributing towards the spectral shape.*

3 IONIZATION RATE

Next, we wish to constrain the NST12 spectrum by determining a low energy cutoff below ~ 1 GeV after comparing with the observed molecular ionization rate.

Normalizing the spectrum derived by NST12 to the PAMELA flux above 200 GeV, and given the observed PAMELA flux at the energy bin centering 213.23 GeV to be $(4.17 \pm 0.08 \pm 0.2) \times 10^{-7} \text{ cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1} \text{ GeV}^{-1}$ (Adriani et al. 2011), we adopt the following spectrum for the diffuse

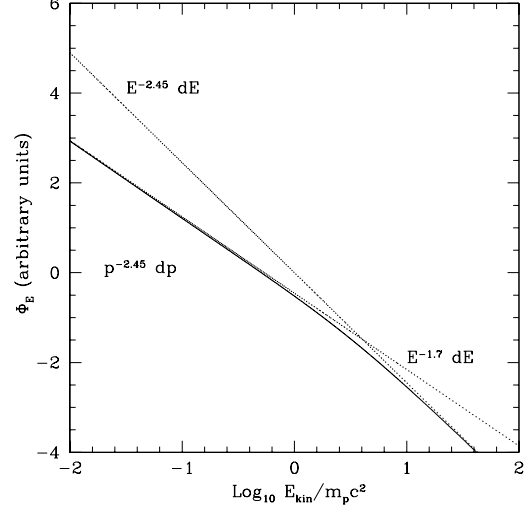


Figure 1. CR proton energy spectra are shown with fluxes in arbitrary units, against kinetic energy in the units of rest mass energy. The solid lines shows a spectrum with constant power-law in momentum (with an index -2.45), and the dotted lines show the asymptotic behaviour at low and high energy ends.

Galactic CR protons:

$$\begin{aligned} & \frac{dN_p}{dE_p} \\ &= 4.17 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1} \left(\frac{E_p}{213.23 \text{ GeV}} \right)^{\Gamma_2}, \\ & \quad E_p \geq E_b \\ &= 4.17 \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1} \\ & \quad \times \left(\frac{E_b}{213.23 \text{ GeV}} \right)^{\Gamma_2} \left(\frac{E_p}{E_b} \right)^{-\Gamma_1}, \quad E_p < E_b \\ & 0, E_p \leq E_{low} \end{aligned} \quad (1)$$

We follow Padovani et al. (2009) in our calculation of the ionization rate of molecular and atomic hydrogen. Only the direct ionization by primary protons is significant and dominates over other processes such as ionization by CR electrons and electron capture by CR protons by more than an order of magnitude. The ionization rate of H_2 by primary protons is,

$$\zeta^{H_2} = \int_{E_{low}}^{\infty} \frac{dN_p}{dE_p} \sigma_p^{ion}(E_p) dE_p, \quad (2)$$

where $\frac{dN_p}{dE_p}$ is the CR proton spectrum at a given kinetic energy E_p and E_{low} is the low energy limit of E_p . The cross-section σ_p^{ion} is given in Padovani et al. (2009). We also multiply this ionization rate by a factor 5/3 in order to take into account the ionization by secondary electrons (Spitzer & Tomasko 1968, Dalgarno & Griffing 1958).

The helium nuclei associated with the CR protons will enhance the ionization of the ISM molecules. In order to assess the enhancement factor introduced by the addition of helium nuclei, we use the ratio of protons to helium nuclei as a function of kinetic energy per nucleon as determined by PAMELA down to a 0.4 GeV/n, and use the proton spectrum of NST12 down to the same value of kinetic energy. We found that the ratio of proton to helium flux in PAMELA data (Adriani et al. (2011) can be fit to an accuracy of $\sim 10\%$

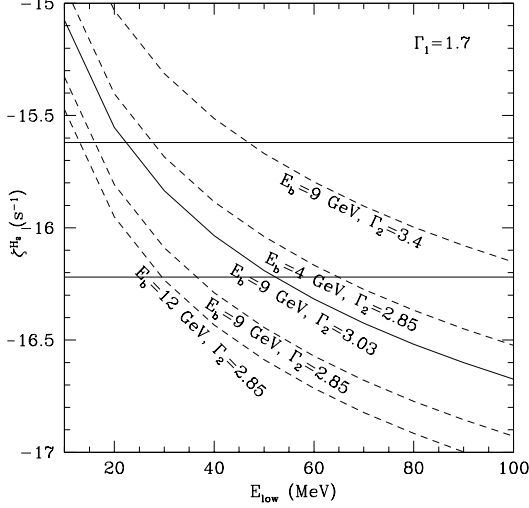


Figure 2. The molecular ionization rate ζ^{H_2} is calculated for the spectrum mentioned above, as a function of the low energy cutoff E_{low} , for a few combinations of the parameters E_b and Γ_2 . The low energy spectral index Γ_1 has been fixed at 1.7.

to the lowest kinetic energy (per nucleon) bin in their tables S3 and S4, by the following expression:

$$\frac{\Phi(p)}{\Phi(He)} \approx 4.47 + 12.68 \tanh(\epsilon/2.247 \text{ GeV}), \quad (3)$$

where $\epsilon = E_k/A$ is the kinetic energy per nucleon. This ratio becomes constant above a value of $\epsilon \geq 20$ GeV/n, and decreases at lower energies.

We find that the ionization rate increases by a factor 1.48 if helium nuclei are included, using the ratio of p/He along with the NST12 spectrum, for a low energy cutoff of 0.4 GeV/n. We note that the p/He ratio as determined by PAMELA may however be affected by solar modulation, and therefore the enhancement of ionization may also be affected. If the low energy is shifted to 1 GeV/n, then the ionization rate increases by a factor 1.33, and for a cutoff at 10 GeV/n, the corresponding factor is 1.23. We note that these factors are somewhat lower than the standard factor of 1.8 used in literature (e.g., Rimmer et al. 2011). Keeping this uncertainty in mind, we multiply the ionization rate of protons by a factor 1.5 below in order to take helium nuclei into account.

We show in **Figures 2 and 3** the corresponding ionization rate ζ^{H_2} as a function of the low energy cutoff, E_{low} , and also show the observed range of $\sim 0.6\text{--}2.4 \times 10^{-16} \text{ s}^{-1}$, for the rates in diffuse clouds with low molecular content (Gerin et al. (2010); Neufeld et al. (2010)). We choose this range since the propagation effects are least likely to affect in the case of low density diffuse clouds. The curves show the ionization rates for different combinations of E_b and Γ_2 , but with $\Gamma_1 = 1.7$ in Figure 2 and $\Gamma_1 = 1.9$ in Figure 3. We note that NST12 derived a value of $\Gamma_1 = 1.7$ in the case of maximal bremsstrahlung component, and provides an extreme limit.

The curves in Figure 2 and 3 show that the ionization rates are somewhat lower in the case of $\Gamma_1 = 1.7$ than for $\Gamma_1 = 1.9$. Also, we find that the cor-

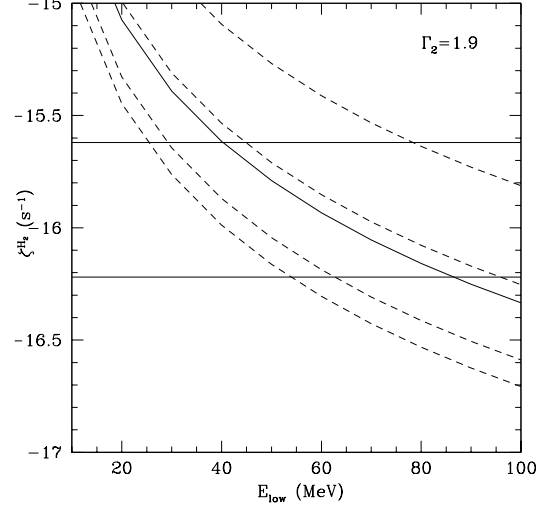


Figure 3. Same as Figure 2 except for Γ_2 being fixed at 1.9.

responding values of E_{low} ranges between $\sim 10\text{--}100$ MeV, for the average $\zeta^{H_2} \sim 0.6\text{--}2.4 \times 10^{-16} \text{ s}^{-1}$ for diffuse clouds with low molecular content. We note that Schuppan et al. (2012) in their determination of the CR spectrum for MCs associated with SNRs, did not add the bremsstrahlung component, and therefore their predicted high ionization rate is likely to be an overestimate.

4 DISCUSSION

The low energy cutoff E_{low} can arise from a number of effects, and we would like to discuss these possibilities here.

4.1 Propagation effects

The low energy cutoff E_{low} is related to the quantity of matter (grammage) the CRs traverse on average in the Galaxy, and the ionization losses suffered by the protons below $E_p \leq E_{low}$. The ionization loss for protons traversing the ISM is given by eqn 4.22 of Mannheim & Schlickeiser 1994,

$$\frac{dE_p}{dt}(\beta) = 4.96 \times 10^{-19} \text{ erg s}^{-1} (n_e/\text{cm}^{-3}) \frac{\beta^2}{\beta^3 + x_m^3}, \quad (4)$$

where $x_m = 0.0286(T/2 \times 10^6 \text{ K})^{1/2}$, T and n_e are the ambient (electron) temperature and density, and $\beta = v/c$. The ionization loss increases rapidly with decreasing proton energy.

For low temperature ISM gas, this ionization loss of protons can also be expressed in terms of the grammage ($\sim nm_p \beta ct$) as $\frac{\Delta E_p}{E_p} \sim \frac{6.7 \times 10^{-2}}{\beta^2(\gamma-1)} \left(\frac{\text{grammage}}{10 \text{ g cm}^{-2}} \right)$, where γ is the Lorentz factor. If we identify the cutoff energy E_{low} as due to ionization loss, then the inferred grammage for $E_{low} = 10(50)$ MeV is $\sim 0.03(0.80) \text{ g cm}^{-2}$. The grammage for a 100 MeV proton is $\sim 3 \text{ g cm}^{-2}$.

The average grammage inferred for GeV cosmic rays in our Galaxy is $\sim 10 \text{ g cm}^{-2}$ (e.g., Brunetti & Codino 2000). This grammage is believed to be smaller for lower energy protons, and go down to $\sim 3 \pm 1 \text{ g cm}^{-2}$, for $E_{kin} \leq 100$

MeV, and also decrease with higher energies (e.g., see Fig 7 in Garcia-Munoz et al (1987)). Interestingly, this estimate of grammage inferred from the secondary/primary ratio is close to the grammage inferred from the interpretation of low energy cutoff of 10–100 MeV from ionization rate, as discussed above. This is our primary result, that using the NST12 spectrum allows us to identify the low energy cutoff with ionization rate, in the sense that the grammage inferred from B/C ratio at this energy coincides with the grammage expected from ionization loss. That this near equality is difficult to achieve with other CR spectrum is evident. If we were to assume a CR spectrum without a flattening down to a low energy cutoff, with a spectral index ~ 2.85 – 3 ., then the Galactic average ionization rate would constrain the low energy cutoff to ~ 250 – 350 MeV. However, if this were to be identified as arising from ionization loss, then the corresponding grammage would be 15 – 30 gm cm^{-2} , much larger than even the peak grammage at GeV scale. Therefore our result shows that NST12 spectrum is consistent with the average Galactic ionization rate with a corresponding grammage of CR protons at low energy arising from ionization loss.

Previous workers (Indriolo et al. (2009); Becker et al. (2011)) have used a low energy cutoff of ~ 2 MeV for diffuse clouds, and 10 MeV for dense clouds. It has been argued that the range of a 1 MeV proton is 8.5×10^{-4} g cm^{-2} , corresponding to a column density of $\sim 5 \times 10^{20}$ H cm^{-2} . Indriolo et al. (2009) considered a low energy cutoff of 2 MeV for diffuse clouds with density $\leq 10^3$ cm^{-3} , and Becker et al. (2011) assumed a low energy cutoff of 10 MeV for molecular clouds near SNRs, with density $\geq 10^3$ cm^{-3} . Here also, the idea has been to find a consistency between the CR spectrum, the low energy cutoff and the ionization rate. However, the calculations mentioned here have either assumed a CR spectrum (and found the ionization rate) or found a CR spectrum for a given ionization rate. At times finding a convergence has been difficult. For example, Indriolo et al (2009) found that their model CR spectrum that took propagation of CRs in the Milky Way produced a lower ionization rate than observed, and they suggested the presence of an additional component of low energy CRs. Our result here shows that with the NST12 spectrum, a convergence of low energy cutoff, grammage and ionization rate is possible.

Also, our results show that even for diffuse clouds a low energy cutoff below 10 MeV is inconsistent with the Galactic average ionization rate, and that the low energy cutoff lies in the range of 10–100 MeV. Therefore, the cutoff in dense molecular clouds is likely to be larger than this value, and our results suggest that the ionization rate in molecular clouds with SNRs, as in Becker et al. (2011), is likely to be an overestimate because of the assumption of a low value of cutoff.

Interestingly, in the model of Biermann et al. (2001), the CR protons from SNR shocks in ISM are expected to have a grammage of ~ 1 gm cm^{-2} , similar to the convergence value found in our analysis. CRs from massive star supernovae are believed to consist of mainly heavy nuclei and their spallation products, while supernovae of moderate mass stars produce predominantly CR protons. The secondary CRs produced in the spallation interactions of massive star supernovae with stellar wind material, are expected

to have a much larger grammage. Therefore our results support the acceleration of CR protons in SNR shocks in ISM.

4.2 Magnetic field effects

Cesarsky & Völk (1978) proposed that CR streaming instability in the presence of magnetic field in MCs would excite Alfvén waves which would scatter off low energy CRs (Skilling & Strong 1976). They estimated that this would screen the MCs from Galactic low energy CRs, and that the low energy cutoff would be related to the cloud size (R), particle density n and magnetic field B , as

$$E \sim 50 \text{ MeV } (R/8.2 \text{ pc})^{0.5} (n/2 \times 10^3 \text{ cm}^{-3})^{0.5} (B/50 \mu\text{G})^{-0.5}. \quad (5)$$

This shows that for a typical MC magnetic field of a few μG (Curran & Chrysostomou 2007), the low energy cutoff can be as large as ≥ 100 MeV. However, if we turn the argument around, then given the typical values of E_{low} derived above for CRs inside MCs imply that the ability of magnetic fields to screen low energy CRs in MCs is smaller than previously thought, since it is clear that in order to sustain the typical average ionization rate in MCs, $E_{\text{low}} \leq 100$ MeV.

5 SUMMARY

In summary, we have studied the Galactic CR proton spectrum recently inferred from gamma ray emission from molecular clouds near Gould’s belt. We have identified the inferred break of the energy spectrum at a few GeV as a consequence of (a) the source CR spectrum being a power-law in momentum, of $p^{-2.45}$, and (b) the diffusion coefficient for protons being independent of energy below a few GeV. We have shown that this renders the CR spectrum consistent with that observed at high energies. We have also derived a low energy cut-off for the CR spectrum, after comparing with the observed Galactic ionization rate of molecular hydrogen (since the ionization is dominated by protons), and found its values to lie in the range of 10–100 MeV. We have then shown that the NST12 spectrum is consistent with three independent phenomena: (a) ionization loss that corresponds to a particular value of grammage, (b) grammage as inferred from other means, and (c) the average Galactic ionization rate.

We thank the anonymous referees for their comments that helped to improve the paper.

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